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A New Limit on CPT Violation *

S. Geer, J. Marriner, M. Martens, R.E. Ray, J. Streets, W. Wester

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

M. Hu, G.R. Snow

University of Nebraska, Lincoln, Nebraska 68588

T. Armstrong

Pennsylvania State University, University Park, Pennsylvania 16802

C. Buchanan, B. Corbin, M. Lindgren, T. Muller†

University of California at Los Angeles, Los Angeles, California 90024

R. Gustafson

University of Michigan, Ann Arbor, Michigan 48109

(The APEX Collaboration)

Abstract

A search for antiproton decay has been made at the Fermilab Antiproton Accumulator. Limits are placed on fifteen antiproton decay modes. The results are used to place limits on the characteristic mass scale m_X that could be associated with CPT–violation accompanied by baryon number violation.

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The CPT theorem requires that the proton (p) and antiproton ($\overline{p}$) lifetimes are equal. Searches for p decay have yielded lower limits on the p lifetime $\tau_p > O(10^{32})$ yr [?]. A search for $\overline{p}$ decay with a short lifetime ($\tau_{\overline{p}} << \tau_p$) tests the CPT theorem. In this paper we summarize results from a search for $\overline{p}$ decay at the Fermilab Antiproton Accumulator, and discuss limits on the characteristic mass scale m_X associated with CPT–violation. For a mass dimension–5 CPT violating operator these limits approach the Planck scale.

CPT invariance is one of the most fundamental symmetries of modern physics. There have been a variety of searches [?,?,?,?] for CPT violation based upon comparing particle and antiparticle masses, lifetimes, and magnetic moments. For example, the p and $\overline{p}$ masses have been shown to be equal with a precision of a few parts in 10^8 [?], while the particle and antiparticle masses in the neutral kaon system have been shown to be equal to about one part in 10^{18} [?,?]. A search for $\overline{p}$ decay complements these CPT tests by providing a search for CPT violation accompanied by a violation of baryon number. Indeed, since the $\overline{p}$ is the only very long–lived antiparticle that could in principle decay into other known particles without violating charge conservation, a search for $\overline{p}$ decay provides a unique test of the CPT theorem, and a unique test of the intrinsic stability of antimatter.

The sensitivity of a $\overline{p}$ decay search to the presence of a CPT violating interaction has been characterized by considering a dimension-n CPT-violating quantum field operator ($n > 4$) with characteristic mass scale m_X. Dimensional analysis then provides the estimate [?] $m_p \tau_{\overline{p}} \sim [m_p/m_X]^{2n-8}$, yielding :

$$m_X/m_p \sim [4.5 \times 10^{38} \cdot \tau_{\overline{p}}/10 \text{ Myr}]^{1/(2n-8)} \ . \qquad (1)$$

For a given lower limit on $\tau_{\overline{p}}$ the implied lower limit on m_X is most stringent for $n = 5$. Note that if m_X is at the Planck scale (1.2×10^{19} GeV/c^2) and $n = 5$, the expected $\tau_{\overline{p}}$ would be $\sim$ 10 Myr.

The most stringent lower limit on $\tau_{\overline{p}}$ has been obtained [?] from a comparison of recent measurements of the cosmic ray $\overline{p}$ flux [?] with predictions based on expectations for secondary production of antiprotons in the interstellar medium. The agreement between the observed and predicted rates implies that $\tau_{\overline{p}}$ is not small compared to T/γ, where T is the $\overline{p}$ confinement time within the galaxy ($\sim 10^7$ yr) and γ is the Lorentz factor for the observed antiprotons. After taking into account the uncertainties on the relationship between the interstellar $\overline{p}$ flux and the flux observed at the Earth, at 90% C.L. the limit $\tau_{\overline{p}} > 8 \times 10^5$ yr has been reported [?]. This indirect limit is not valid if current models of $\overline{p}$ production, propagation, and interaction in the interstellar medium are seriously flawed. For example, within the minimal supersymmetric extension to the standard model, a significant cosmic ray $\overline{p}$ flux can be produced by cold dark matter neutralino annihilation. In this scenario, if the depletion of the spectrum due to $\overline{p}$ decay is compensated by additional contributions from neutralino annihilation, it has been claimed [?] that the current cosmic ray data can accommodate $\overline{p}$ lifetimes as low as $\leq 10^5$ years.

Laboratory searches for $\overline{p}$ decay have, to date, provided less stringent limits on $\tau_{\overline{p}}$. However, these limits do not suffer from large model dependent uncertainties. The most stringent published laboratory limit on inclusive $\overline{p}$ decay has been obtained from a measurement of the containment lifetime of ~ 1000 antiprotons stored in an ion trap, yielding $\tau_{\overline{p}} > 3.4$ months [?]. The sensitivity of laboratory $\overline{p}$ decay searches can be improved by looking for explicit $\overline{p}$ decay modes at a $\overline{p}$ storage ring. Angular momentum conservation requires that a decaying $\overline{p}$ would produce a fermion (electron, muon, or neutrino) in the final state. A search for explicit $\overline{p}$ decay modes with an electron in the final state was made by the T861 experiment at the Fermilab Antiproton Accumulator. The T861 search yielded the 95% C.L. limits [?]: $\tau_{\overline{p}}/B(\overline{p} \rightarrow e^-\gamma) > 1848$ yr, $\tau_{\overline{p}}/B(\overline{p} \rightarrow e^-\pi^0) > 554$ yr, $\tau_{\overline{p}}/B(\overline{p} \rightarrow e^-\eta) > 171$ yr, $\tau_{\overline{p}}/B(\overline{p} \rightarrow e^-K^0_S) > 29$ yr, and $\tau_{\overline{p}}/B(\overline{p} \rightarrow e^-K^0_L) > 9$ yr.

Following the T861 results, the APEX experiment [?] was designed to enable a more sensitive search for $\overline{p}$ decay. The APEX detector, located in a straight section of the 474 m circumference Fermilab Antiproton Accumulator ring, was designed to identify $\overline{p}$ decays within a 3.7 m long evacuated decay tank. Particles exiting the tank at large angles to the circulating $\overline{p}$ beam traversed a 96 cm diameter 1.2 mm thick stainless steel vacuum window. The experiment was optimized to detect a single energetic charged track (electron or muon), originating from the beam, and accompanied by one or more neutral pions or photons. A detailed description of the detector can be found in Ref. [?]. In brief, the detector consists of (i) An upstream system of scintillation counters arranged around the 10 cm diameter beam pipe, located upstream of the tank, and used to reject upstream interactions. (ii) Three planes of horizontal and three planes of vertical scintillation counters downstream of the tank. Each plane consisted of two $50 \times 100 \times 1.27$ cm^3 counters. The last counter planes were downstream of a 2.3 radiation length lead wall, providing a preradiator to aid in identifying electrons and photons. The first and second counter planes, upstream of the lead, provided pulse height information used to count the traversing charged particles. (iii) A lead–scintillator sampling electromagnetic calorimeter [?] constructed from 144 rectangular 10×10 cm^2 modules that are 14.7 radiation lengths deep, arranged in a 13×13 array with 6 modules removed from each of the four corners, and the central module removed to allow passage of the beam pipe. (iv) A tail catcher (TC) downstream of the calorimeter consisting of a 20 cm deep lead wall followed by two planes of scintillation counters. (v) A muon telescope (MT) downstream of the TC, 10 nuclear interaction lengths deep, and aligned to point towards the center of the decay tank. The MT consists of a sandwich of five iron plates and five 30×30 cm^2 scintillation counters, and was used to identify penetrating charged particles (muon candidates). (vi) A tracking system consisting of three planes of horizontal and three planes of vertical 2 mm diameter scintillating fibers downstream of the tank and upstream of the preradiator lead. These detectors provided three space points along the track trajectory with typical residuals of 620 μm in the directions transverse to the beam direction, enabling the origin of tracks emerging from the decay tank to be reconstructed with an rms precision given by $\sigma_z = 12$ cm.

The APEX experiment took data at times when there were typically 10^{12} antiprotons circulating in the Accumulator ring with a central $\overline{p}$ momentum of 8.90 ± 0.01 GeV/c ($\gamma = 9.54 \pm 0.01$). A measure of the sensitivity of the APEX data sample is given by:

$$S \equiv \frac{1}{\gamma} \int N_{\overline{p}}(t)\, dt = (3.31 \pm 0.03) \times 10^9 \;\; yr, \tag{2}$$

where $N_{\overline{p}}(t)$ is the number of circulating antiprotons at time t, the integral is over the live-time of the experiment, and the uncertainty arises from the precision with which the time dependent beam current was recorded.

Energetic particles passing through the detector during Accumulator operation predominantly arise from interactions of the $\overline{p}$ beam with the residual gas in the decay tank or with material surrounding the beam. To suppress these backgrounds, and select candidate $\overline{p} \to \mu^- X$ and $\overline{p} \to e^- X$ decays, signals from the calorimeter and the scintillation counters were used to form an MT trigger which recorded 1.2 $\times 10^6$ events, and calorimeter triggers which recorded 37.8 million events. Offline, events were selected for analysis if they had (i) a single charged track reconstructed in the tracking system that pointed back to the beamline within the fiducial volume of the decay tank, and (ii) a pattern of hits in the scintillation counters and calorimeter cells consistent with a 2-body or 3-body $\overline{p}$ decay topology. Events that passed these requirements were then required to be kinematically consistent with the particular decay channel being considered (see Table 1). A detailed description of the triggers, data taking, and analysis can be found in Refs. [**?**,**?**,**?**,**?**]. No statistically significant $\overline{p}$ decay signal was observed. For a specific decay mode with branching ratio B this null result can be used to place a limit on τ/B which is given in years by:

$$\tau_{\overline{p}}/B(\overline{p} \to \mu^- X) \ > \ - \frac{1}{ln(1 - N_{max}/\epsilon S)} \ , \tag{3}$$

where ϵ is the calculated fraction of decays taking place uniformly around the accumulator ring that pass the trigger and event selection requirements. The upper limit on the number of signal events N_{max} is given by the prescription of Ref. [**?**]:

$$N_{max} \ = \ \mu_{max} \times (1 + \mu_{max} \ \sigma_r^2/2) \ , \tag{4}$$

where $\sigma_r \equiv \sigma_\epsilon/\epsilon$, σ_ϵ is the systematic uncertainty on ϵ, and μ_{max} is the 90% C.L. upper limit corresponding to the observation of N events that pass the trigger and selection requirements. A detailed Monte Carlo simulation of the detector geometry and response has been used to calculate ϵ and σ_r.

Table 1 lists the resulting limits on τ/B for 15 decay modes in which there is an electron or muon in the final state. Our results are shown in Fig. **??** to be significantly more stringent than previous limits [**?**]. In particular, we place the first explicit limits on the muonic decay modes of the $\overline{p}$, and the first limits on the decay modes $e^-\gamma\gamma$, $e^-\rho$, $e^-\omega$, and $e^-K^{0^\star}$. Our most stringent limit is on the decay $\overline{p} \to e^-\gamma$ for which we find $\tau/B > 7 \times 10^5$ yr (90% C.L.). Table 2 summarizes the limits on the CPT–violating mass scale derived from Eq. (1), listed as a function of the mass dimension–n for $5 \leq n \leq 9$. Note that for the most sensitive decay modes the lower limit on m_X is O(10^{18}) GeV/c^2 for $n = 5$. For $n = 6$ the limits are in the range $10^8 - 10^9$ GeV/c^2 for all 15 decay modes. Even for $n = 8$ the limits on m_X are still at the 10 TeV/c^2 scale. These are unique limits on the presence of CPT–violation accompanied by a violation of baryon number.

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† Present address: Universität Karlsruhe, 76128 Karlsruhe, Germany.

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TABLES

TABLE I. Summary of results: 90% C.L. limits on τ/B for 15 antiproton decay modes.

Decay Mode	τ/B Limit (years)	Decay Mode	τ/B Limit (years)
$\mu^-\gamma$	5×10^4	$e^-\gamma$	7×10^5
$\mu^-\pi^0$	5×10^4	$e^-\pi^0$	4×10^5
$\mu^-\eta$	8×10^3	$e^-\eta$	2×10^4
$\mu^-\gamma\gamma$	2×10^4	$e^-\gamma\gamma$	2×10^4
$\mu^-K_L^0$	7×10^3	$e^-K_L^0$	9×10^3
$\mu^-K_S^0$	4×10^3	$e^-K_S^0$	9×10^2
		$e^-\rho$	2×10^2
		$e^-\omega$	2×10^2
		$e^-K^{0\star}$	1×10^3

TABLE II. Summary of limits on the CPT–violating scale m_X (GeV/c^2) shown as a function of the mass dimension–n of the associated quantum field operator.

Decay Mode	n				
	5	6	7	8	9
$\mu^-\gamma$	1×10^{18}	1×10^{9}	1×10^{6}	3×10^{4}	4×10^{3}
$\mu^-\pi^0$	1×10^{18}	1×10^{9}	1×10^{6}	3×10^{4}	4×10^{3}
$\mu^-\eta$	6×10^{17}	7×10^{8}	8×10^{5}	3×10^{4}	3×10^{3}
$\mu^-\gamma\gamma$	9×10^{17}	9×10^{8}	9×10^{5}	3×10^{4}	4×10^{3}
$\mu^-K_L^0$	5×10^{17}	7×10^{8}	8×10^{5}	3×10^{4}	3×10^{3}
$\mu^-K_S^0$	4×10^{17}	6×10^{8}	7×10^{5}	2×10^{4}	3×10^{3}
$e^-\gamma$	5×10^{18}	2×10^{9}	2×10^{6}	5×10^{4}	5×10^{3}
$e^-\pi^0$	4×10^{18}	2×10^{9}	2×10^{6}	4×10^{4}	5×10^{3}
$e^-\eta$	9×10^{17}	9×10^{8}	9×10^{5}	3×10^{4}	4×10^{3}
$e^-\gamma\gamma$	9×10^{17}	9×10^{8}	9×10^{5}	3×10^{4}	4×10^{3}
$e^-K_L^0$	6×10^{17}	7×10^{8}	8×10^{5}	3×10^{4}	3×10^{3}
$e^-K_S^0$	2×10^{17}	4×10^{8}	5×10^{5}	2×10^{4}	3×10^{3}
$e^-\rho$	9×10^{16}	3×10^{8}	4×10^{5}	2×10^{4}	2×10^{3}
$e^-\omega$	9×10^{16}	3×10^{8}	4×10^{5}	2×10^{4}	2×10^{3}
$e^-K^{0\star}$	2×10^{17}	4×10^{8}	6×10^{5}	2×10^{4}	3×10^{3}

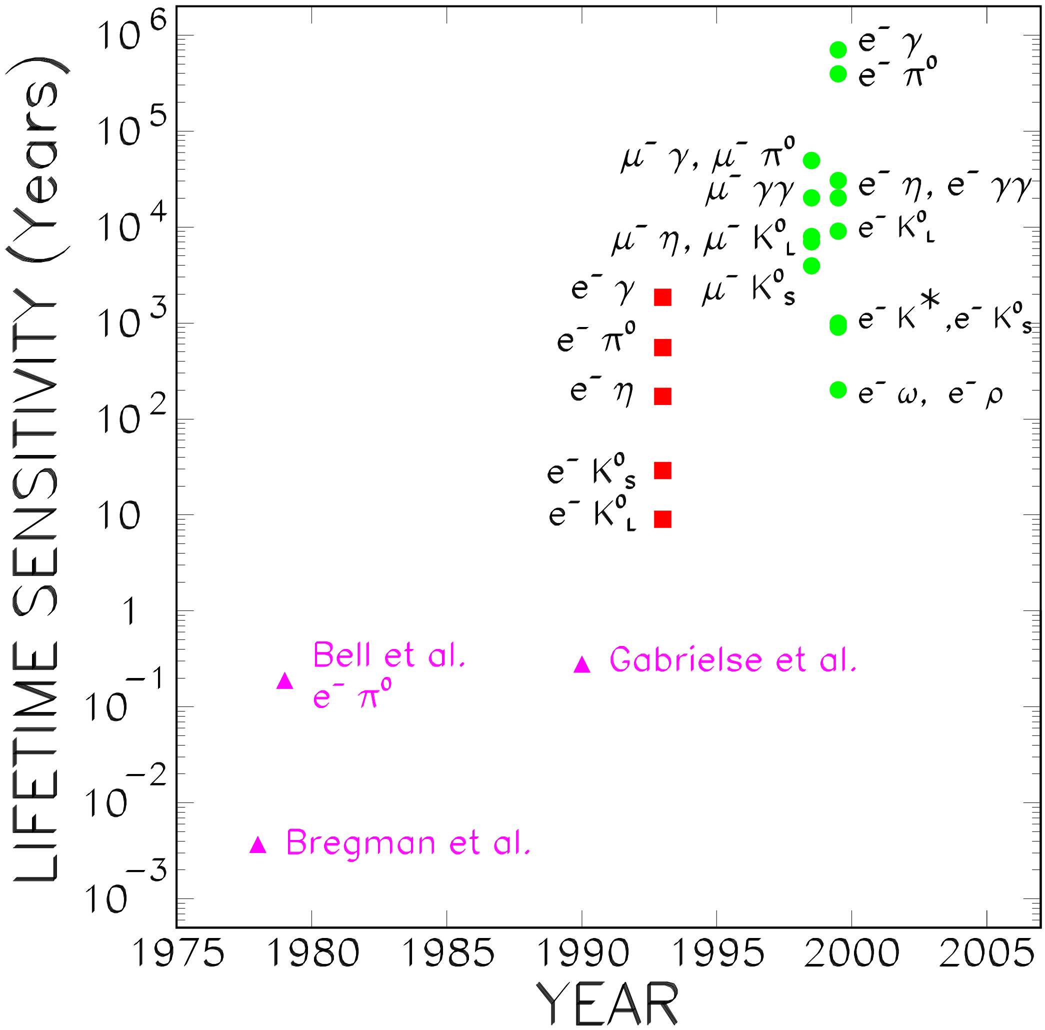

FIG. 1. Upper limits on the antiproton lifetime. APEX limits (circles), T861 limits (boxes), and limits [?,?,?] prior to the T861 experiment (triangles) are shown as a function of the publication year.